

Research Paper

Evaluating climate change adaptation strategies and scenarios of enhanced vertical and horizontal compactness at urban scale (a case study for Berlin)

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ABSTRACT

This study evaluates the effectiveness of climate change adaptation strategies in Berlin, Germany, on a summer day by using the urban climate model MUKLIMO_3. White coating, green roofs and a combination of both are analysed regarding their cooling ability on the 2-m-temperature. Additionally, horizontal and vertical compactness are evaluated in terms of their respective impact on the micro climate. An enhanced albedo of the urban surfaces leads to the highest cooling ability with a significant daily average cooling of 0.2 K per 0.1 increase of albedo, while green roofs have only a small cooling effect at pedestrian level. An increased vertical compactness has a cooling ability due to the higher amount of shading, enhanced horizontal compactness shows a negative impact on the micro climate due to the raised percentage of sealed surfaces and the additional urban structures that can emit additional heat during the night. All strategies show a higher effect on the daytime and a smaller influence on the nocturnal temperature.

1. Introduction

Near surface air temperature is warming since the 19th century (Hansen et al., 2006). Both the ocean and atmosphere show unambiguous increases in their respective temperatures. The increasing temperature have a drastic impact on the biosphere of our planet. The main cause for global warming is the elevated output of greenhouse gases by humans (Pachauri et al., 2014). The fourth quarter of the last century showed a significant increase of heat related extreme events, while the increase of the mean temperature reached 0.11 K per decade in the period from 1946–99 (Klein Tank & Können, 2003). In the region of Berlin-Brandenburg, Germany, the mean temperature rose over 1 K in the last century with a decrease in the number of frost days about 17 and an increase of summer days of about 12 (Cubasch & Kadow, 2011).

The high temperatures have a large impact on human health. Heat waves are among the natural disasters that have the highest mortalities. Infants, elder and sick people suffer most from the thermal load, because their bodies' ability to adapt to extreme conditions has either been weakened or not yet fully developed (Jendritzky, 2007). The thermal conditions scales up the temperature even further in big cities. During extensive heat waves in the years of 1990 and 2006, the mortality rates were especially high in densely built-up areas in Berlin (Gabriel & Endlicher, 2011). Other European cities, for example Budapest, London, Milan, show similar increases in mortality rates during heat waves (Ishigami et al., 2008). The

intensity and the occurrence of heat waves in Europe will rise even more in the 21st century (Kovats and Hajat, 2008; Meehl & Tebaldi, 2004).

The main reason for such high temperatures in big cities compared to their surroundings is the urban heat island (Oke, 1973). The characteristic elements of a natural landscape like meadows, trees and forests, give way to buildings, industrial areas and infrastructure, which have fundamentally different physical characteristics. The high percentage of sealed surfaces and the artificial geometry of urban structures manipulate the urban climate due to an increased specific heat capacity and thermal conductivity, altered albedo and radiative trapping (Oke, 1988; Rizwan, Dennis, & Liu, 2008). Additionally, due to reduced vegetation, the decreased evapotranspiration leads to less cooling of the air by lesser energy demand for the phase transition of water (latent heat) and subsequently to an increase of the temperature (Grimmond, Salmond, Oke, Offerle, & Lemonsu, 2004; Taha, 1997). All of these effects lead to higher temperatures during the night, when stored solar energy is emitted to its environment.

Urban heat islands will have more negative impacts through more frequent and more intensive heat waves in the future (Fallmann, Wagner, & Emeis, 2017). There are measures and possibilities to mitigate the urban heat island. Examples being the rise of albedo of different urban surfaces for a higher amount of reflection of incoming solar radiation and thus less heat storage in buildings, the increase of vegetation, and hybrid scenarios of the two. While increasing the albedo is only a strategy to reduce the near surface temperature, a higher vegetation fraction has other benefits such as

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increased evapotranspiration, which leads to cooling, and its role as a sink for CO₂ (Akbari & Kolokotsa, 2016; Lynn et al., 2009; Susca, Gaffin, & Dell'Oso, 2011; Santamouris, 2014; Sodoudi et al., 2014; Taha, 1997).

The increased urbanization poses a second problem for temperatures in big cities (Schmelcher et al., 2014). The size of a city and its urban heat island show a proportional coherence (Oke, 1973). Apart from the urban sprawl, there are two other options to generate additional living space in a city: vertical and horizontal compactness. These two scenarios have dissimilar effects on the urban micro climate, such as affecting the wind speed and temperatures in the street canyons (Dodman, 2009; Taleghani, Kleerekoper, Tenpierik, & den Dobbelsteen, 2015; Van Hove et al., 2015). While the first measure requires the addition of storeys to already existing buildings, the second scenario can be realized with additional buildings.

The aim of this work is to evaluate the strategies of climate change adaptation for Berlin. Scenarios with increased roof vegetation, higher albedo of urban surfaces and combined strategies will be evaluated regarding their impact on the 2 m-temperature. Furthermore, the two possibilities for additional living space, vertical and horizontal compactness, are analysed with regards to their impact of the urban climate of Berlin. While vertical compactness can be achieved by altering the height of already existing buildings, the second scenario is realized by implementing buildings on the open spaces in Berlin (Fig. 1: open spaces = wastelands: LU classes 36, 37, 38). Both can be done with the urban climate model MUKLIMO_3, developed by the German Weather Service (Sievers, 1995).

2. Methods & data

The urban climate model MUKLIMO_3 was developed to evaluate diurnal cycles of different meteorological parameters such as temperature, wind, relative humidity, and radiation, with a horizontal resolution of about 100 m depending on weather conditions, land use (LU) data, and topography (Früh et al., 2011; Sievers, 2016). The wind is calculated with the equation of motion of the air. The necessary integration of that equation is done with the stream function method (Sievers, 1995). The model parametrizes unresolved buildings and vegetation in a double averaging of the equation of motion, and calculates the long-wave and short-wave radiation within the domain (Sievers, 2012; Sievers, 2016). In order to run the model, a series of characteristic parameters for each land use class need to be

calculated first (Früh et al., 2011). These parameters indicate: the percentage of grid cell covered by buildings, mean building height, wall-area index, percentage of grid cell covered by sealed surfaces, albedo of the roofs, albedo of the walls, albedo of the sealed surfaces, percentage of the roof covered with vegetation, roughness length, mean tree height, leaf area density for the tree crown, mean stem height, leaf area density in stem height, height of the low vegetation canopy layer, leaf area index for the canopy layer, percentage of grid cell covered by tree canopy, and percentage of grid cell covered by low vegetation. All of these variables can be derived from the urban atlas of Berlin (SenStadt, 2011) and the Corine Land Cover dataset (European Environment Agency, 2010). They are specified for each LU class in a table for the external land cover parameters – the urban table. Two important features of the model are that there cannot be trees and buildings in the same grid cell and that MUKLIMO_3 cannot simulate the phase transition of water in the atmosphere. Consequently, precipitation or the forming of clouds cannot be simulated. All simulations in this study were performed with MUKLIMO_3 version 141010.

June 25, 2010 was chosen as the simulation day on the account of it being a summer day, where the maximum temperature exceeds 25 °C. MUKLIMO_3 requires a set of meteorological input for its simulations. They form the basis for an intermediate 1-dimensional model, which calculates the boundary conditions, i.e. incoming radiation and temperature at the upper boundary of the model domain, as well as the initialization data for the 3-dimensional simulations of MUKLIMO_3. The 1-dimensional model is forced by daily average values for cloud cover, wind speed and wind direction. Additionally, up to 5 vertical layers of air temperature and relative humidity can be used for the initialization of the 1-dimensional model. The meteorological forcing is derived from a rural point outside the city, since it should represent the conditions in the surroundings. Therefore, the weather station Schönefeld from Germany's National Meteorological Service (DWD), situated in the southeast of Berlin, was chosen to provide the daily mean values for wind speed (2.4 m/s at 10 m height), wind direction (NNW), and cloud cover (3/8). The vertical profiles for temperature and relative humidity initialization were simulated with the mesoscale Weather Research and Forecasting Model (WRF), which was developed by the National Center for Atmospheric Research (NCAR) (Skamarock, Klemp, Dudhia, & Gill, 2008). As it is the aim of this study to analyse the near surface conditions and their changes, the 5 lowest vertical layers computed with WRF are used

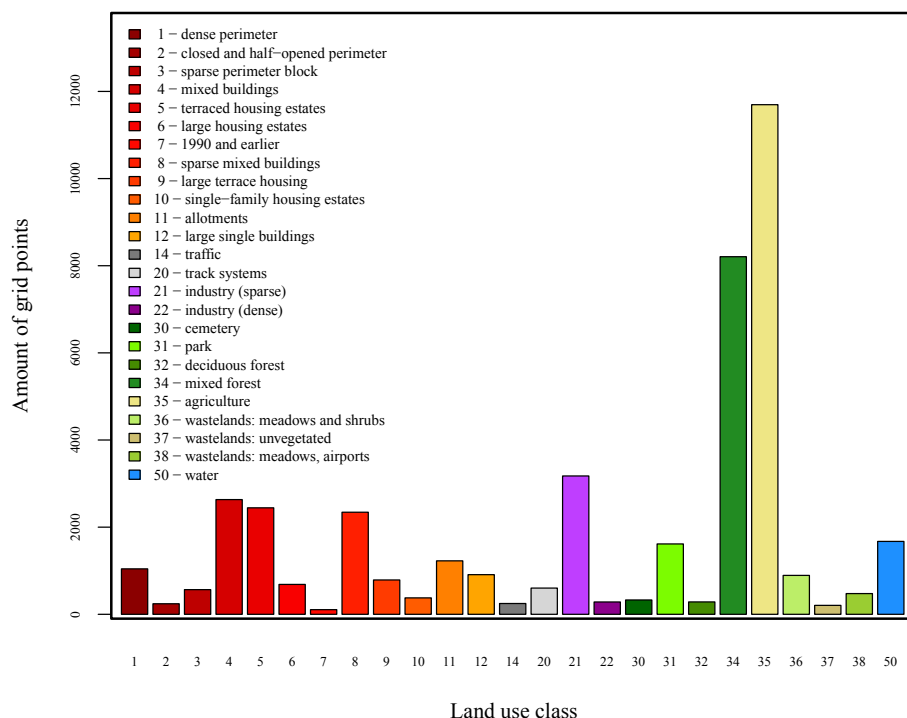


Fig. 1. Amount of grid points per different land use class for the study area of Berlin. Each grid point represents a 200 × 200 m square. The total amount of grid points in this study is 188 × 229 = 27022. The land use file used for the simulations with MUKLIMO_3 contains 25 classes, of which 15 contain buildings (1–12, 14, 21, 22). The LU classes 36, 37 and 38 are considered as open spaces for the scenarios of horizontal compactness.

Table 1

Changes of respective parameters in the urban table for the different scenarios. The scenarios “Green roofs”, “White coating” and “Hybrid scenarios” evaluate changes in all building classes. The default values for each parameter are listed in the first column and in [table 1](#) of the appendix ([Sievers, 2016](#)).

Strategies	Percentage of roof covered with vegetation	Albedo of the roofs, walls, and sealed surfaces
Green roofs (G1, G2, G3)	33%	–
(default: vegetation = 0%)	66%	–
	99%	–
White coating (W1, W2, W3)	–	0.33
(default: albedo = 0.3)	–	0.66
	–	0.99
Hybrid scenarios (H1, H2, H3)	33%	0.33
(default: vegetation = 0%; albedo = 0.3)	66%	0.66
	99%	0.99

to initialize MUKLIMO_3 (from 10.4 m to 825 m above sea level). The horizontal grid resolution chosen for this study is 200 m. This gives sufficient possibilities to evaluate the different strategies on micro scale while keeping the computation time of MUKLIMO_3 to a minimum. Two different

LU datasets have been used in this study. The land use from the urban atlas indicates the classes for Berlin ([SenStadt, 2011](#)) and the CORINE Land Cover dataset provides the LU classes for the surroundings ([European Environment Agency, 2010](#)). A total of 25 different LU classes are included in the dataset, 15 of them include buildings ([Fig. 1](#)).

During the validation of the model, several sensitivity tests have been done. The default values for several input parameters of MUKLIMO_3 were changed to improve the quality of the results ([Sievers, 2016](#)). Adjusted parameters include the soil temperature, the water temperature, the soil moisture class, and the type of soil. For a detailed setup of the baseline conditions (default values) for the MUKLIMO_3 simulations, see [Table A1](#) in the appendix. For the scenarios of adaptation, the application of white coating, green roofs, and hybrid strategies, the respective values for the albedo of roofs, walls and surfaces as well as the percentage of the roof covered by vegetation were altered in the urban table for all building classes in the city ([Table 1](#)). The study about vertical compactness was done with a change of height and wall-area index for three building classes (LU1-3) in the urban table. The scenarios for horizontal compactness were realized with an implementation of buildings on open spaces within the city borders that are currently not built-up (open spaces = wastelands: LU classes 36, 37, 38) ([Table 2](#)).

The statistical measures used for the evaluation of the model MUKLIMO_3 are the Pearson correlation coefficient, root mean square

Table 2

Changes of respective parameters in the urban table for the different scenarios. The scenario for “Horizontal compactness” simulates buildings on open spaces (LU classes 36, 37, 38) and for “Vertical compactness” only the respective parameters of the building classes 1–3 were altered. The default values for each parameter are listed in the first column and in [table 1](#) of the appendix ([Sievers, 2016](#)).

Strategies	Wall-area index (WAI)	Mean building height (hb)	Building surface fraction (vg1)
Horizontal compactness (HC1)	7.5	17 m	0.6
(default: open spaces = no buildings)			
Vertical compactness (VC1, VC2, VC3)	8.8, 11.2, 10.4	20 m	–
(default: WAI = 7.5, 7.3, 7.0; hb = 17 m, 13 m, 13.5 m, vg1 = 0.6, 0.4, 0.5)	13.2, 16.8, 15.6	30 m	–
	17.6, 22.5, 20.7	40 m	–

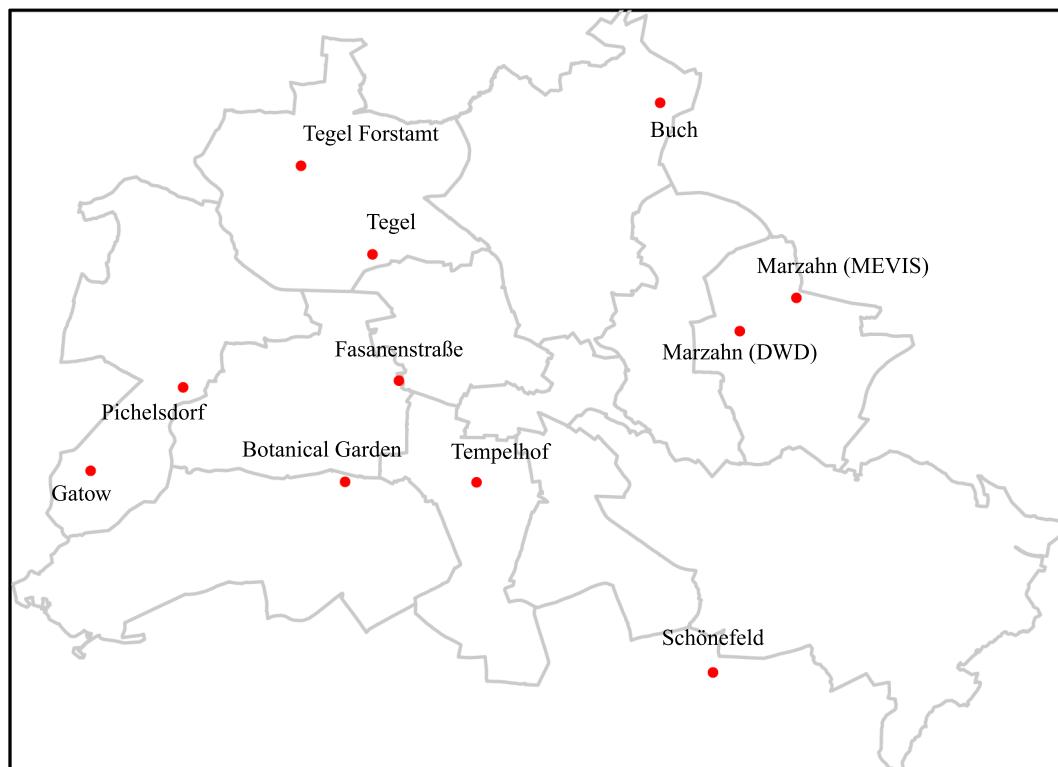


Fig. 2. Model domain for the simulations with MUKLIMO_3 and location of 11 Weather stations in Berlin used for the validation of the model.

error (RMSE), and mean error (ME), respectively. Eleven weather stations located in Berlin were used to determine the quality of the simulation (Fig. 2). From these initial 11 stations, 10 were selected after the model validation because they are representative for the LU class which they are situated in. The strategies for adaptation are evaluated in terms of their cooling effect compared to the reference scenario considering the Lilliefors test for analysing the distribution of the datasets and the Wilcoxon signed-rank test for determining the

significance of the differences in the medians of the 2 m-temperature between the various scenarios (Conover, 1980). Statistical significance is achieved with $p < 0.05$.

3. Results

All simulations were done with a horizontal resolution of 200 m, starting at 9 a.m. on June 25, 2010 and ending at 9 a.m. on June 26,

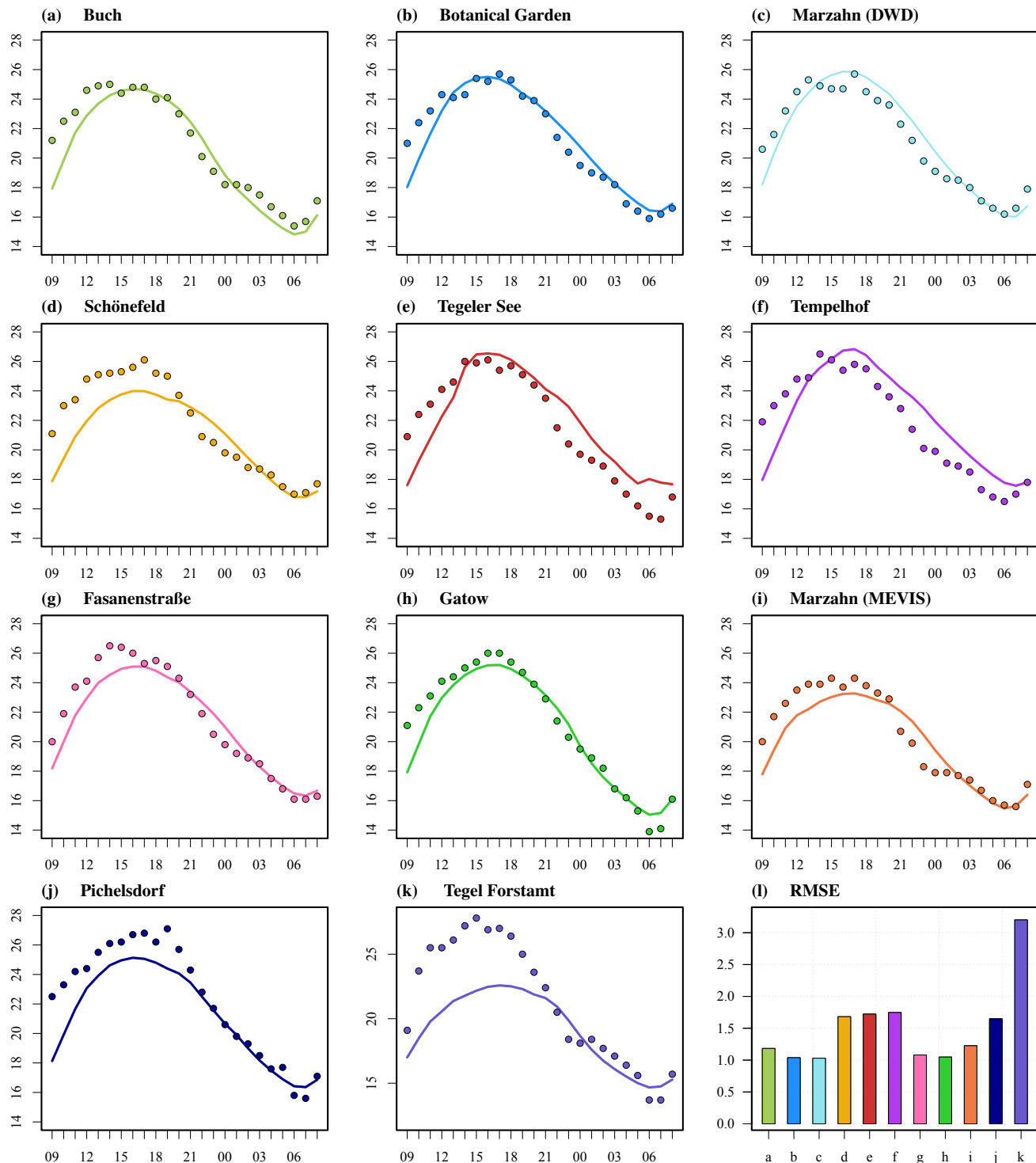


Fig. 3. Comparison of measurement (points) and simulation (lines) of 2 m-temperature at June 25, 2010, in degrees centigrade for eleven measuring stations in Berlin used in this study. The RMSE of the simulation for each of the stations is shown in the bar plot on the bottom right side. The colours of the different graphs are meant to differentiate between the different stations and do not represent certain land use classes.

2010, to obtain a diurnal cycle for the 2 m-temperature at each grid point. The results will be analysed in three steps. The 2 m-temperature at 3 p.m. (daytime), 2 a.m. (night-time), and the mean diurnal range are evaluated to get information about the model simulations during daytime, night-time, and the whole day. For the evaluation of the different scenarios, the changes in the 2 m-temperature will be compared to the reference scenario at 3 p.m. and 2 a.m., both in the altered grid cells and on the whole simulation area of Berlin. In the analysis of the strategies to generate more living space in Berlin, the changes of the wind at 2 m height are also considered.

3.1. Model validation

The first part of the work with MUKLIMO_3 was a validation. In this process, the results of the simulations of the model were compared to measurements from meteorological stations in Berlin. The aim was to adapt MUKLIMO_3 from its default settings for Berlin on a summer day. To achieve that, several input parameters were altered to get realistic surface characteristics or meteorological input (Appendix – Table A1). Such were the soil moisture class (slightly dry soil), soil type (sandy loam), water temperature (18 °C) and soil temperature (18 °C). The latter proved to be the parameter with the strongest effect on the quality of the simulations of MUKLIMO_3, while the soil moisture class also had a substantial influence on the results. The more moisture the soil contained, the more latent heat flux is produced. After the adjustment of the model to Berlin, the simulations of the mean 2 m-temperature showed a RMSE of 1.3 K and a significant correlation coefficient of 0.9, while underestimating the mean 2 m-temperature by 0.3 K (Fig. 3).

The weather stations which were chosen for the validation of Berlin are in good accordance with the measurements (Fig. 3). Fig. 3 highlights two problems of MUKLIMO_3. After sunset, the model cannot reproduce the actual cooling, which contributes to the high values for RMSE and the overestimation of the 2 m-temperatures. There could be several reasons for this disparity. The principal factor is the cloud cover which was input as a constant 3/8 for the simulation period. The actual observations at the weather station Schönefeld show a higher cloud cover during the day and a lower cloud cover during the night. This leads to a high amount of outgoing radiation at night-time, causing the stronger cooling observed after sunset. There can be other causes for the differences between observation and simulation which should to be analysed in more detail.

While most simulations at the meteorological stations are in good agreement with the measurements, others show great differences between model output and measured data (Fig. 3). The station Tegel Forstamt (k), which is located in a forest in the north of Berlin, and serves as an example to clarify potential differences between measurements and simulations. The meteorological station is located at a

clearing and therefore is exposed to direct sunlight during daytime. The respective grid cell of MUKLIMO_3, which has a horizontal resolution of 200 m, does not show this clearing, but instead is covered by forest. Subsequently, the model does not simulate direct sunshine on the ground due to the dense forest canopy and as a result cannot reproduce the high temperatures during daytime, leading to a high RMSE (3.2). By contrast, the station at the Botanical Garden (b), is simulated with a low RMSE (1.0 K) (Fig. 3). That is because the model grid cell does share the same specifications as the location in which the meteorological station is actually on. It is important when evaluating an urban climate model with a certain resolution that the measuring station is located in a place that is representative for its surroundings and that the specifics of the grid cell comply with those of the station. For this reason, the station Tegel Forstamt was not included in the calculation of the RMSE for the model.

The distribution of the 2 m-temperature for 3 p.m. and 2 a.m. show the differences between the temperatures in the city and its surroundings (Fig. 4). While these variations between urban and rural areas are close to 8 K during the day (a), at night time they increase up to 12 K (b). The left side of the figure clearly shows the distributions of dense built-up areas with higher temperatures (yellow and red) and quarters of vegetation and forest and water bodies with lower temperatures at 3 p.m. (green and blue). The distinct features of Berlin, the three big forests in the northwest (Tegeler Forst (1)), the southwest (Grunewald (2)), and the southeast (Stadtforst Berlin-Köpenick (3)) are clearly visible, as are the parks (e.g. Tiergarten (4)) and great open spaces (e.g. Tempelhofer Feld (5)). Another notable feature of Berlin is the LU of its surroundings, which is dominated by agriculture. This is why most parts outside the municipal borders are warmer than the forests of Berlin. The right side of Fig. 4 shows the very high temperatures over the city at night. According to the average wind direction (NNW) measured at the weather station Berlin-Schönefeld and used for model forcing, cool air is advected from the north northwest and the hot air is transported to the south.

3.2. Adaptation strategies

Different scenarios have been applied in this study to reduce the mean air temperature at 2 m height. This is achieved by increasing the roof vegetation and the albedo of the urban surfaces. Higher near surface temperature is one of the impacts of climate change, which is further intensified by the urban heat island phenomenon (Fallmann, Emeis, & Suppan, 2014; Oke, 1973). Reducing the near surface temperature contributes to climate change adaptation and urban heat island mitigation. This can be achieved with a higher reflection of incoming solar radiation and thus a reduction of the stored heat that can be released during the night. The increase of inner city vegetation enhances evapotranspiration, brings cooling and acts as a sink for CO₂

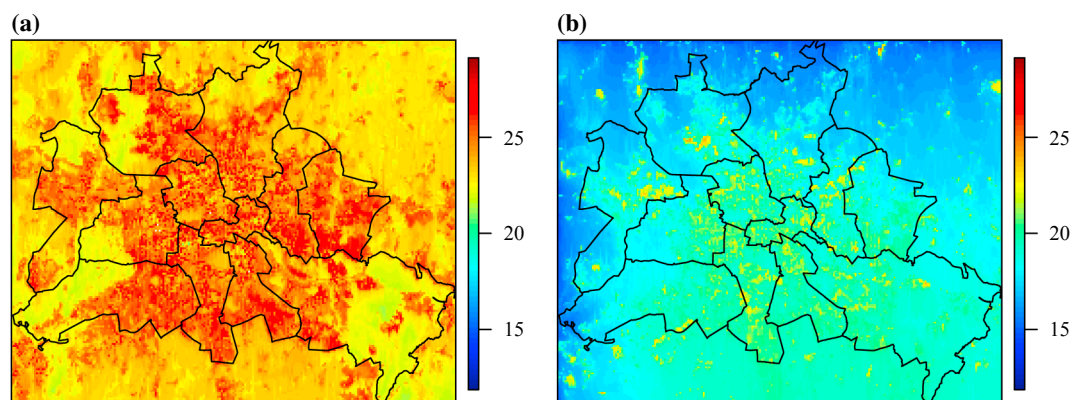


Fig. 4. Distribution of 2 m-temperature at 3 p.m. on June 25, 2010 (a) and at 2 a.m. on June 26, 2010 (b) in degrees centigrade.

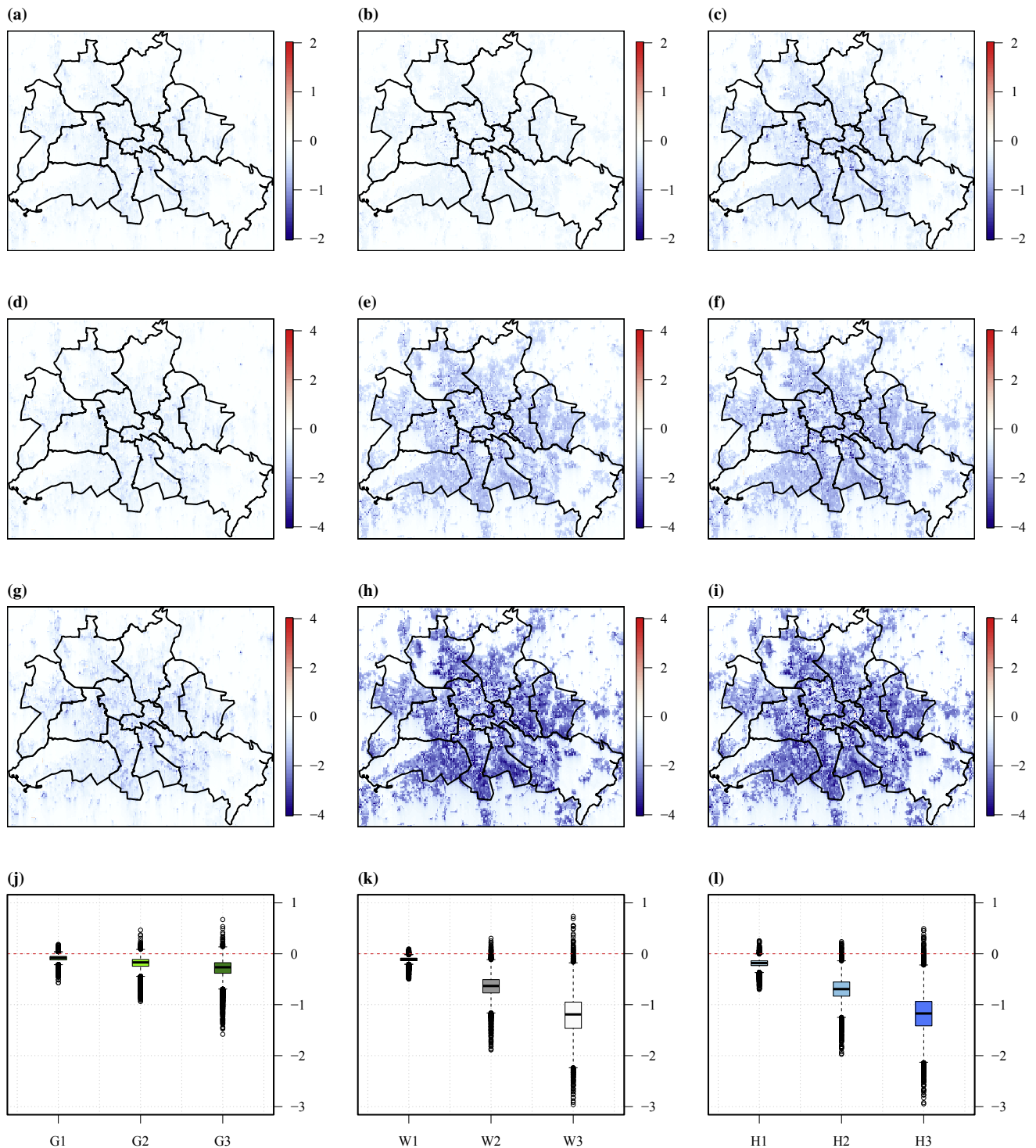


Fig. 5. Results of the simulations of the adaptation strategies. The 9 temperature distribution maps show the difference in 2-m-temperature at 3 p.m., the boxplots show the change in the diurnal mean 2-m-temperature on June 25, 2010, between the reference simulation and the respective scenario in degrees centigrade. The colour coding of the boxes symbolizes the extend of the scenario, going from light to dark green or blue for the green roof and the hybrid scenario and from dark grey to white for the white coating scenario. The left column shows the results for fraction of green roof: (a): 0.33, (d):0.66, and (g):0.99 (default: 0%). (j) shows the mean decreases of the three scenarios in 2-m-temperature over the whole day in Kelvin. The middle column shows the results for the white coating scenarios: (b): albedo = 0.33, (e): albedo = 0.66, and (h): albedo = 0.99. (k) shows the mean decreases of the three scenarios in 2-m-temperature over the whole day in Kelvin. The right column shows the results for the hybrid scenarios: (c): fraction of green roof = 0.33 and albedo = 0.33, (f): fraction of green roof = 0.66; and albedo = 0.66, and (i): fraction of green roof = 0.99 and albedo = 0.99. (l) shows the mean decreases of the three scenarios in 2-m-temperature over the whole day in Kelvin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Akbari & Kolokotsa, 2016). These scenarios have been evaluated in terms of their mean diurnal, daytime and nocturnal cooling. The application of the adaptation strategies was done by changing the

respective parameters in the urban table, which are an input for MUKLIMO.3 (Table 1). There are parameters for the percentage of a roof that is covered by vegetation and for the albedo of facades, roofs,

Table 3

Mean differences in 2 m-temperature of different strategies of adaptation, both for the modified land use (LU) classes only and the whole model area, given in Kelvin. The statistical significance according to the Wilcoxon signed-rank test is realized with $p < 0.05$ (marked by *).

Strategies	Mean cooling in modified LU classes at 3 p.m. [K]	Mean cooling in modified LU classes at 2 a.m. [K]	Mean cooling in modified LU classes in 24 h [K]	Mean cooling in the model domain in 24 h [K]
(a) G1: green roofs = 0.33	0.2 (*)	0.0 (*)	0.1 (*)	0.1 (*)
(b) G2: green roofs = 0.66	0.4 (*)	0.0 (*)	0.2 (*)	0.1 (*)
(c) G2: green roofs = 0.99	0.6 (*)	0.1 (*)	0.3 (*)	0.2 (*)
(e) W1: albedo = 0.33	0.2 (*)	0.0 (*)	0.1 (*)	0.1 (*)
(f) W2: albedo = 0.66	1.2 (*)	0.3 (*)	0.6 (*)	0.4 (*)
(g) W3: albedo = 0.99	2.1 (*)	0.6 (*)	1.2 (*)	0.7 (*)
(i) H1: Hybrid (0.33)	0.4 (*)	0.1 (*)	0.2 (*)	0.1 (*)
(j) H2: Hybrid (0.66)	1.3 (*)	0.3 (*)	0.7 (*)	0.4 (*)
(k) H3: Hybrid (0.99)	2.1 (*)	0.6 (*)	1.2 (*)	0.6 (*)

and surfaces. For each of the three strategies of adaptation, these values were raised in three steps: 0.33, 0.66, and 0.99. The respective changes were done in all 15 LU classes that contained buildings. The mean decreases of the 2 m-temperature achieved with the various strategies are noted in Table 2 and shown in Fig. 4. All results of the scenarios are significant according to the Wilcoxon signed-rank test which is realized with $p < 0.05$.

The left column of Fig. 5 shows the results for the scenarios with implemented green roofs at 3 p.m. (Fig. 5(a)–(d)). The boxplot implies that green roofs have little effect on the mean 2 m-temperature, which can be attributed to the height of the buildings on which the vegetation has been put on (Williamson, Parker, & Kendrick, 1989). While the vegetation might cool the air at the roof level, the ground is scarcely effected by it (Buchholz, Kossmann, & Roos, 2016; Santamouris, 2014). Apart from the slight cooling effect of green roofs, they have other ramifications on the climate in the city. Urban vegetation in general acts as a sink for air pollutants, increases the biodiversity, retains rainwater and reduces the ozone concentration of the city (Akbari & Kolokotsa, 2016; Fallmann, Forkel, & Emeis, 2016). These effects cannot be simulated with MUKLIMO_3, though. The overall significant cooling of green roofs rises about 0.2 K per

0.33 increase of fraction of roof vegetation at 3 p.m. and about 0.1 K per 0.33 increase of fraction of roof vegetation averaged over the whole day (Table 3, (a)–(c)). No cooling was simulated during the night. Other researches emphasized on the negligible effects of green roofs in Tokyo or Hong Kong (Chen, Ooka, Huang, & Tsuchiya, 2009; Ng, Chen, Wang, & Yuan, 2012).

In the middle column of Fig. 5, the results for the idealized scenarios with white coating for all urban surfaces are shown (Fig. 5, (e)–(h)). The reference values of albedo for the different surfaces are roofs = 0.3, facades = 0.3, sealed surfaces = 0.25). The repercussions of a higher albedo on the mean 2 m-temperature are noticeably higher than with green roofs (Fig. 5, (h)). Due to the increased reflection of incoming solar radiation, less energy can be absorbed by the urban structures. This leads to both reduced daytime heating and less heating of the air due to stored energy from the buildings at night-time. MUKLIMO_3 simulates a significant mean decrease in the 2 m-temperature of 0.2 K per 0.1 rise of albedo averaged over the whole day (Table 3, (e)–(g)). The rise of the albedo has a notable impact on the 2 m-temperature on the whole model domain. The cooling effect of white coating is high enough to also significantly affect their adjacent grid cells. Other studies show similar results for scenarios of white coating. The INKAS project simulated a similar cooling for high albedo scenarios during daytime and night-time with MUKLIMO_3 for typical urban settlements (Buchholz et al., 2016). An average cooling of 0.5 K was simulated for Berlin using COSMO-CLM with an urban parametrization called Double-Canyon Effect Parametrization, while changing the albedo of all surfaces from 0.16 to 0.65 (Schubert & Grossman-Clarke, 2013). Compared to the second white coating scenario in this study, where the albedo was increased by about 0.3, led to a decrease of 0.6 K in the mean average temperature. Similar results were presented for New

York using the Penn State/NCAR MM5 regional climate model, where an average cooling of 0.3 to 0.7 K was simulated for light coloured surfaces (Rosenzweig et al., 2006). The mean cooling of 0.2 K per 0.1 rise of albedo is consistent with that from a study in New York using also the Penn State/NCAR MM5 regional climate model (Lynn et al., 2009). The computed values for this scenario do agree with those from the review of Santamouris (2014).

The right column of Fig. 5 displays the cooling potential of the combined scenarios of green roofs and white coating (0.33, 0.66, and 0.99) (Fig. 5, (i)–(l)). The results are similar to the simulated decrease of the 2 m-temperature with the white coating scenario. This implies that the cooling in the hybrid scenarios happens mainly due to the rise in albedo and not because of the increased roof greenery. The hybrid scenario has other advantages, which are already mentioned as benefits for green roofs. The mean cooling is 0.2 K per 11% increase in vegetation and 0.1 rise in albedo. Other studies indicate, that the hybrid strategies are the most effective strategies because they are combined climate change adaptation and urban heat island mitigation strategies (Schubert & Grossman-Clarke, 2013; Sodoudi, Shahmohamadi, Vollack, Cubasch, & Che-Ani, 2014).

3.3. Vertical & horizontal compactness

The aim of the designed scenarios for vertical or horizontal compactness is to evaluate possible ways of creating more living space within the city of Berlin, without extending the municipal borders. In both scenarios the aspect ratio of the street canyons is altered: for vertical compactness, the canyon height is increased and for horizontal compactness, the canyon width is decreased. This is realized by either adding storeys to the existing buildings of LU class 1, 2, and 3 (Fig. 1), which cover about 6800 ha or 5% of the model domain or implementing buildings of LU class 1 (building height: 17 m, building surface fraction: 0.6) onto the open spaces (LU36–38) within the city (HC). These open spaces are defined in the input data (European Environment Agency, 2010; SenStadt, 2011) as not built-up, with a low sealed surface fraction (LU36 and LU37: 0.05; LU38: 0.3) and either sparsely vegetated by 20% (LU37) or covered with low vegetation by 90% (LU36 and LU38). They add up to roughly 6000 ha, which is about 4% of the model domain of Berlin. For the vertical compactness scenarios, the buildings were risen to 20 m (VC1), 30 m (VC2), and 40 m (VC3), from their real heights of 17 m (LU class 1), 13 m (LU class 2), and 13.5 m (LU class 3). The wall-area indices were adapted to the new heights. All results of the scenarios are significant according to the Wilcoxon signed-rank test which is realized with $p < 0.05$. The simulation for horizontal compactness shows a mixed result for the 2 m-temperature at 3 p.m. (Fig. 6, (a)). While there are areas, where a decrease of up to 2 K is simulated, in other parts the 2 m-temperature rises as far as 2 K. Altogether the scenario leads to a minor cooling of 0.2 K during the day (Table 4). At night (b), the additional buildings have a large heating effect. While open spaces have a high amount of outgoing radiation and low heat storage, the simulated additional buildings work

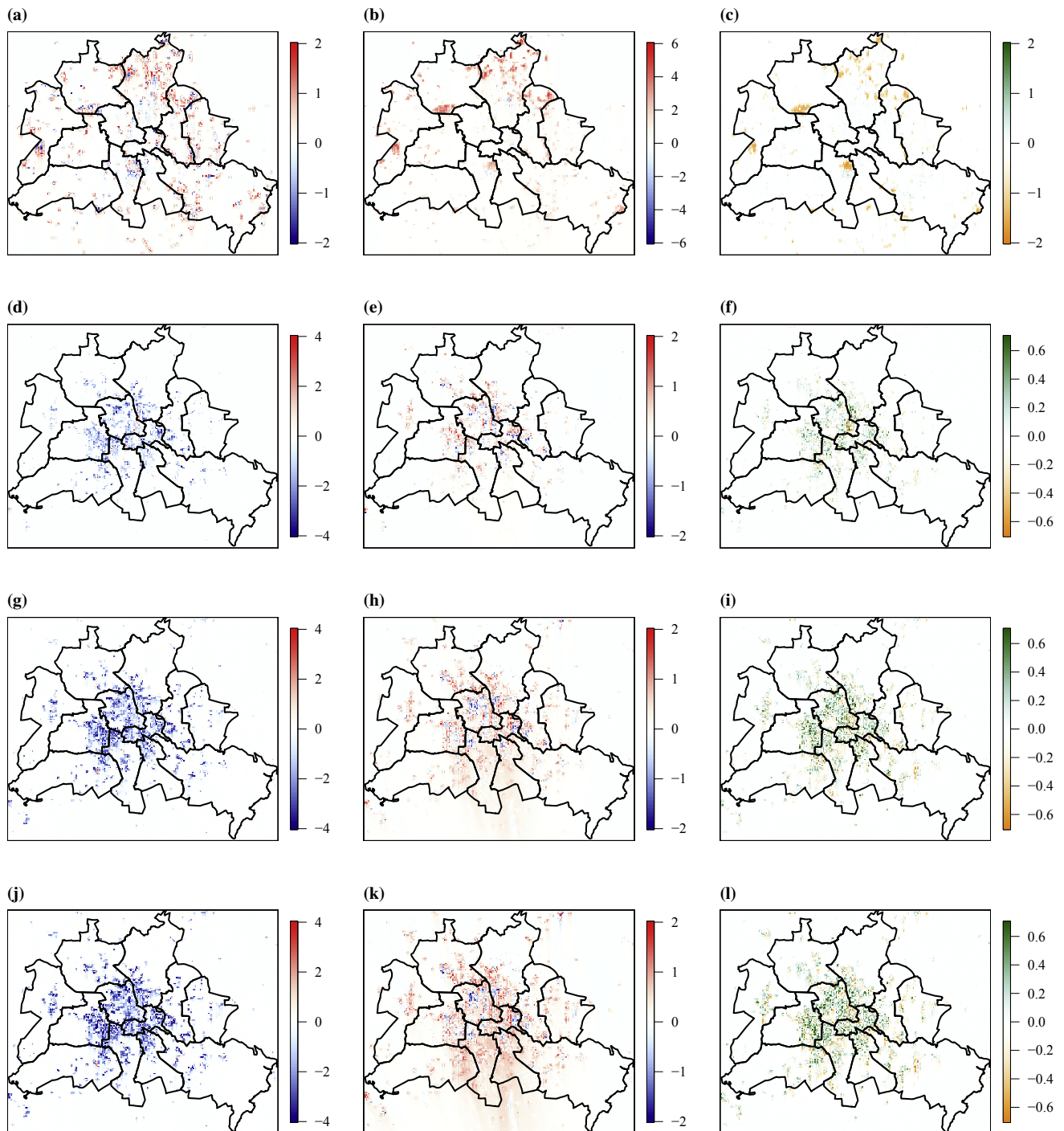


Fig. 6. Cooling potential of 2 m-temperature and mean change of the wind in 2 m height for the scenarios for increased compactness in Kelvin and m/s, respectively. The first row shows the results of 2 m-temperature for horizontal compactness at 3 p.m. (a) and 2 a.m. (b) and wind at 3 p.m. (c). The second row shows the results of 2 m-temperature for vertical compactness (20 m) at 3 p.m. (d) and 2 a.m. (e) and wind at 3 p.m. (f). The third row shows the results of 2 m-temperature for vertical compactness (30 m) at 3 p.m. (g) and 2 a.m. (h) and wind at 3 p.m. (i). The fourth row shows the results of 2 m-temperature for vertical compactness (40 m) at 3 p.m. (j) and 2 a.m. (k) and wind at 3 p.m. (l).

in the opposite way and lead to increased temperatures of 2.2 K at 2 a.m. This results in a daily mean increase in 2 m-temperature of about 0.8 K. The scenarios for vertical compactness offer a large cooling ability during daytime due to the increased shading of higher buildings (d,g,j) and higher wind speeds (f,i,l). During the night, increased temperatures in the altered LU classes are simulated (e,h,k). The reason for this is that higher buildings can store more heat during the day. That

heat is emitted at night time, resulting in an increase of 2 m-temperature of about 0.3 K at 2 a.m. for all scenarios. The daily mean tendency for the scenarios of vertical compactness is a cooling effect. Assuming building heights of up to 40 m, the mean daily 2 m-temperature can be decreased of up to 1 K, with a mean cooling at 3 p.m. about 2.7 K and local decreases of maximum temperatures over 4 K.

When considering the changes of the wind at 2 m height at 3 p.m.

Table 4

Mean differences in 2 m-temperature of different strategies of compactness, both for the modified land use (LU) classes only and the whole model area, given in Kelvin. HC: horizontal compactness, VC 1–3: vertical compactness with resulting building heights of 20 m, 30, and 40 m, respectively. The statistical significance according to the Wilcoxon signed-rank test is realized with $p < 0.05$ (marked by *).

Strategies	Mean cooling in modified LU classes at 3 pm [K]	Mean cooling in modified LU classes at 2 am [K]	Mean cooling in modified LU classes in 24 h [K]	Mean cooling in the model domain in 24 h [K]
HC1 (a), (e)	0.2 (*)	−2.2 (*)	−0.8 (*)	−0.1 (*)
VC1 (b), (f)	1.1 (*)	−0.2 (*)	0.4 (*)	0.0 (*)
VC2 (c), (g)	2.1 (*)	−0.2 (*)	0.8 (*)	0.0 (*)
VC3 (d), (h)	2.7 (*)	−0.3 (*)	1.0 (*)	0.0 (*)

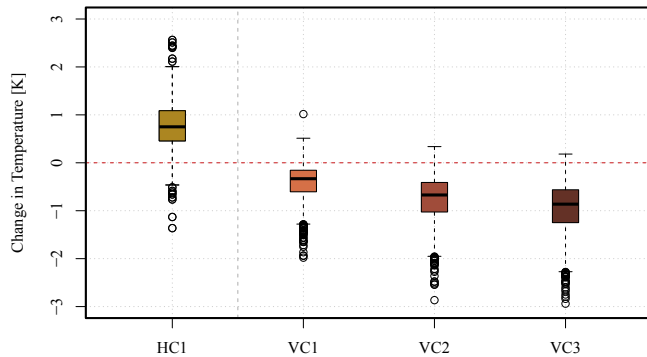


Fig. 7. Mean differences between reference and compactness scenarios for 24-hour simulations in Kelvin. HC1: horizontal compactness, VC1: vertical compactness (20 m), VC2: vertical compactness (30 m), VC3: vertical compactness (40 m).

(c), the scenario for horizontal compactness shows a decrease of up to 2 m/s in the big open spaces of the city. The implemented buildings prevent the generation of high wind speeds near the surface. All scenarios for vertical compactness (f,i,l) result in an increase of the wind of up to 0.6 m/s which could be due to an enhanced canalization effect between the higher buildings. Another reason could be that higher buildings lead to a higher downward turbulent transport of air and consequently a higher wind. The effect of the scenarios of enhanced compactness on the wind at 2 m height during night-time are very similar to the daytime differences. Lower wind speeds can have a positive effect on the human thermal comfort (Penwarden, 1973). When considering hot and calm meteorological conditions, lower wind speeds can have a negative impact on human thermal comfort. The positive effects of vegetated open spaces on the human thermal comfort, noise and air pollution mitigation can also not be neglected (Bruse, 2007; Cohen, Potchter, & Schnell, 2014). They can also serve as places of recreation or social and cultural diversity (Burgess, Harrison, & Limb, 1988). Consequently, it would be more beneficial for a city to turn sealed open spaces into vegetated areas to increase the human thermal comfort.

The scenarios for compactness are summarized in Fig. 7. It shows the boxplots for 4 strategies and indicates that horizontal compactness leads to an overall warming, while vertical compactness has a positive effect on daytime cooling in the city and a warming effect at night-time, depending on the height of the buildings. These findings agree with other studies, where an increased height of the buildings leads to higher shading and less radiation reaching the street level or increased building surface fraction (enhanced horizontal compactness) results in higher air temperatures (Buchholz & Kossmann, 2015; Taleghani et al., 2015).

4. Conclusion

This study is the first to evaluate different idealized adaptation

strategies and idealized scenarios for compactness in Berlin on an urban scale. The urban climate model MUKLIMO_3 was adapted to Berlin and validated with measurements from weather stations in the city and its surroundings. The analysis of these strategies has been done by changing the characteristic parameters in the urban table. After the validation process, MUKLIMO_3 reproduced the measured values for 2 m-temperature at ten chosen weather stations of Berlin with an RMSE of 1.3 K with a mean underestimation of the 2 m-temperature of 0.3 K. The biggest errors of the model are produced in the early hours of the simulation, where the difference between simulation and observation is up to 3 K. The maximum and minimum temperatures have been simulated well. It has to be taken into account that MUKLIMO_3 is not designed to consider changes in synoptic conditions during a simulation, but simulates the impacts of specific land use classes at the micro climate with a constant meteorological situation. Better accordance with observed data could maybe be accomplished, if a more detailed input of weather data would be possible.

Concerning the adaptation strategies, the results of the simulations with MUKLIMO_3 agree with other studies. A high cooling ability of white coating of the urban surfaces with a significant average decrease of 0.2 K per 0.1 increase in albedo, and a weak cooling effect of green roofs with a significant average decrease of 0.1 Kelvin per 10% increased roof vegetation was simulated. The hybrid scenarios show similar results as the scenarios with increased albedo. When only considering the cooling effect for the 2 m-temperature, the strategies with increased albedo show the best solution for mitigating the urban heat island. It has to be considered that a higher amount of reflected short wave radiation has an impact on heat load due to the increase of reflected short wave radiation and hence leads to a rise of the mean radiant temperature (Lee, Mayer, & Schindler, 2014).

The different compactness scenarios address the amount of living space within a city. While not changing the city size as such, two options to increase housing are vertical and horizontal compactness. Of the two, simulations for vertical compactness show a significant decrease in the daytime 2 m-temperatures with a small increase during the night and a strong increase of the wind at 2 m height during daytime, while horizontal compactness leads to a small cooling effect at daytime and a strong increase of 2 m-temperature at night time and a drastic reduction of the wind speed in 2 m height. This scenario also leads to a loss of open spaces within the city. These should remain as such or be turned into parks with a minimal amount of sealed surface to preserve the positive impact of these areas on the micro climate of Berlin and to keep the biodiversity high within the city. Of the two, vertical compactness is the better scenario to create additional living space in a city against the background of human thermal comfort.

For a future study, an analysis of combined scenarios with applied white coating, green roofs, vertical compactness and increased vegetation on open spaces would be interesting. This could be an optimal measure to both generate more housing and also achieve better human thermal comfort. It is suggested to also consider the energy demand of buildings and possibilities to reduce it for an improvement of the micro climate.

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Appendix

Urban Table for reference simulation with MUKLIMO_3. Examples of 3 different LU classes: dense perimeter buildings, forest, and water

* Urban Table for reference simulation of Berlin with MUKLIMO_3	
* Meaning of the parameters:	
* Typ:	code-number of the parameter
* vg1:	Building surface fraction (type 1)
* wail:	wall area index of building (type 1)
* h1:	height of building (type 1) [m]
* vs:	degree of surface sealing (0 to 1) of spaces between the buildings
* vs = −1	grid cell covered by water
* z0:	roughness length of the spaces between the buildings
* hbm:	height of trees [m]
* hst:	height of stem [m]
* lai:	leaf area index of tree canopy
* hca:	mean height of tree canopy in the grid cell [m]
* sigbm:	percentage of grid cell covered by trees
* sigma:	percentage of grid cell covered by surface vegetation
* grant:	percentage of roofs covered by vegetation (default: 0.)
* albw:	mean albedo of walls (default: 0.3)
* albd:	mean albedo of roofs (default: 0.2)
* albvs:	mean albedo of sealed surfaces (default: 0.2)

Table A1

Input parameters for the 3 building classes and the 3 land use classes with open spaces for the reference simulation with MUKLIMO_3 for Berlin. The land use classes LU1-LU3 were used in the scenarios for vertical compactness, LU36-LU38 were modified in the scenario for horizontal compactness.

Name	LU1 Dense perimeter buildings	LU2 Closed and half-opened perimeter	LU3 Sparse perimeter buildings	LU36 Open Spaces <i>meadows and shrubs</i>	LU37 Open Spaces <i>unvegetated</i>	LU38 Open Spaces <i>meadows and airports</i>
Typ	1	2	3	36	37	38
vg1	0.6	0.4	0.5	0.0	0.0	0.0
wail	7.5	7.3	7.0	0.0	0.0	0.0
h1	17.0	13.0	13.5	0.0	0.0	0.0
vs	0.8	0.7	0.6	0.05	0.05	0.2
z0	0.2	0.2	0.2	0.2	0.1	0.1
hbm	0.0	0.0	0.0	0.0	0.0	0.0
hst	0.0	0.0	0.0	0.0	0.0	0.0
lai	1.0	1.0	1.0	1.0	1.0	1.0
hca	0.5	0.5	0.5	1.0	0.2	0.3
sigbm	0.0	0.0	0.0	0.0	0.0	0.0
sigma	0.6	0.6	0.6	0.9	0.2	0.9
grant	0.0	0.0	0.0	0.0	0.0	0.0
albw	0.3	0.3	0.3	0.0	0.0	0.0
albd	0.2	0.2	0.2	0.0	0.0	0.0
albvs	0.2	0.2	0.2	0.0	0.0	0.0

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